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WAVEGUIDE JUNCTION WITH SILICON NITRIDE

The present invention relates to junctions between semiconductor and dielectric waveguides. It relates for example to silicon nitride optical waveguides and in particular to the manufacture of junctions between such waveguides and silicon waveguides, and the use of such junctions, for example, in interferometers.

It is known in the art to provide a silicon on insulator waveguide connected to optical fibres, thus providing a path along which light can propagate. This type of waveguide is useful for many types of optical devices, including interferometers such as a Mach-Zehnder interferometer.

When light is transmitted through a silicon waveguide, some light energy is propagated as an evanescent field outside the geometric boundary of the silicon.

In the case of silicon, the evanescent field is small. The effective refractive index of the waveguide, and hence the phase velocity of any light transmitted through the waveguide, is dependent on the relative values of the refractive index in the material of the waveguide and the refractive index of the surrounding medium in which the evanescent field is propagated. Silicon nitride may also be used for an optical waveguide in the same wavelength ranges as silicon. Silicon nitride has a lower refractive index than silicon and consequently variations in the refractive index of the surrounding medium have a much greater effect on the effective refractive index of a silicon nitride waveguide than is the case for a silicon waveguide. Consequently the use of silicon nitride can be advantageous in applications where sensitivity to variations in surrounding refractive index is required. Such use may be carried out in interferometers and particularly when used to detect the presence of selected external media as may occur in biosensing operations.

In use, one of two branches of the interferometers is immersed in the environment of interest whilst the other branch remains

in the control environment. The effect on the refractive index of the immersed branch can be measured by detection of the interference pattern formed with the light passing through the control branch, the degree of interference affecting the light

5   intensity observed. This is because this intensity depends on the proportion of light maintained within the immersed branch, which in turn alters the effective length of the light path, which directly relates to the refractive index. The proportion of light maintained within the immersed branch depends on the

10   relative difference of refractive index between the branch and its environment and therefore may be affected by, for example, a particular chemical.

However, silicon nitride is not readily formed as a thick enough layer for a waveguide having required structural integrity and

15   thickness for accurate optical alignment with connecting optical fibres. Silicon nitride may also provide problems in single mode propagation if the waveguide is curved.

20   It is an object of the present invention to provide an improved optical waveguide including a silicon/silicon nitride junction.

According to a first aspect of the present invention there is provided a junction structure between a semiconductor waveguide region and a first dielectric forming a further waveguide region

25   of lower refractive index than said semiconductor waveguide region, which structure comprises a light transmitting semiconductor layer having an end face at said junction, and a substrate below the semiconductor layer and extending beyond said

30   junction and a first dielectric light transmitting layer formed over the extending part of the substrate and extending in alignment with the semiconductor layer to provide the further waveguide region, wherein a second dielectric layer of refractive index below that of the two waveguide regions is formed over the

35   end face of the semiconductor and over the extending part of the substrate, thereby forming a support layer of required thickness for the further waveguide region to provide the required

alignment of the optical axis through the two waveguide regions.

According to a second aspect of the present invention there is provided an optical interferometer having parallel light transmitting paths, at least one of said paths including a waveguide junction structure as aforesaid.

According to a third aspect of the present invention there is provided a method of forming a junction structure between semiconductor and a first dielectric in an aligned region of a waveguide, the method comprising the steps of forming a semiconductor waveguide having an end face at said junction on a substrate below a light transmitting semiconductor layer, such that a substrate extension projects beyond said junction, depositing a layer of first dielectric to form a further waveguide region extending over said substrate extension and prior to depositing the first dielectric, depositing a second dielectric layer of refractive index below that of the semiconductor and the first dielectric so that said second dielectric extends over the end face of the semiconductor waveguide and over the substrate extension, thereby forming a support layer for the first dielectric over the substrate . extension, the thickness of the said second dielectric layer providing the required alignment of the optical area through the waveguide.

According to a further aspect of the present invention there is provided a method of biosensing using the interferometer as aforesaid, comprising the steps of; measuring a first interference amplitude with the silicon nitride section exposed to a reference environment, and then exposing the silicon nitride section to a test environment, and measuring a second interference amplitude, and providing a sensing result from selective values of said first and second amplitudes.

An embodiment of the present invention will be described by way of example and with reference to the accompanying drawings in

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which:

Figure 1 shows a sectional structure of a known silicon-on-insulator waveguide;

Figure 2 shows a junction between a silicon-on-insulator waveguide and a silicon nitride waveguide in accordance with the invention;

Figure 3 shows a plan view of a modification of the junction of Figure 2, and

Figure 4 shows an interferometer using a silicon and silicon nitride waveguide in accordance with the present invention.

In the figures, like reference numerals indicate like parts.

Integrated silicon rib waveguides of the type shown in Figure 1 are known. A light transmitting layer of silicon 1 is formed over a buried layer of silicon dioxide 2 on a silicon substrate 3. The silicon layer 1 has an upstanding rib 4 defining an optical transmission path along the waveguide. A layer of silicon dioxide 5 covers the silicon layer 1 and rib 4. The optical profile of light transmitted through the waveguide is shown schematically at 6 although there is an evanescent field which extends outside the silicon rib 4. Further details of this form of waveguide are given in a paper entitled "Low loss single mode optical waveguides with large cross-section in silicon-on-insulator" by J. Schmidtchen et al in Electronic Letters, 27, page 1486, 1999 and in PCT Patent Specification No. WO95/08787.

This form of waveguide provides a single mode, low loss (typically less than 0.2 dB/cm for the wavelength range 1.2 to 1.6 microns) waveguide typically having rib width and height dimensions in the order of 3 to 5 microns which can be coupled to optical fibres and which is compatible with other integrated components.

The speed of light along the waveguide, is dependent on the effective refractive index of the waveguide. This is dependent

on the refractive indices of both the silicon of the waveguide and the medium outside the waveguide through which the evanescent field travels.   Silicon has a refractive index of about 3.5 whereas silicon nitride has a refractive index of only about 2.

5   Consequently the effective refractive index of a waveguide using silicon nitride as the light transmitting medium is much more responsive to variations in the refractive index of the outside medium than is a silicon waveguide.   Consequently, for applications of a waveguide responsive to variation of the

10   external medium, silicon nitride provides advantages over silicon for the light transmitting layer.   However, use of low pressure chemical vapour deposition (LPCVD) to deposit silicon nitride may result in a layer of thickness of the order of 0.2 μm whereas a typical silicon waveguide may conveniently have a thickness of

15   about 4 μm.   Such thin layers of silicon nitride in a waveguide present problems of structural integrity, single mode operation, as well as accurate alignment with any optical fibre system connected to the waveguide.   Furthermore, silicon nitride in such a waveguide does not provide a basis for forming active devices

20   which may respond to application of electric signals to vary the optical transmission in the way that silicon does.

For these reasons, the present embodiment shown in Figures 2 and 3 combines sections of silicon and silicon nitride in an optical

25   waveguide with a junction between silicon and silicon nitride as shown in Figure 2.

The wafer of Figure 2 comprises the silicon-on-insulator waveguide 11 joined to a silicon nitride waveguide 12 at the

30   junction 10 depicted as a sectional view in Figure 2.   In this figure the direction of light travel is left to right.   It may also be operated with light travel from right to left.   The required optical alignment is achieved, which means that the centre of the light mode travelling through the silicon waveguide

35   11 is aligned with the centre of the light mode travelling through the silicon nitride waveguide 12.   This achieves maximum light energy transfer across the junction.   Approximate mode

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field matching is achieved despite the large difference in size
in the vertical direction between the waveguides due to the
difference in refractive indices between the guides which
compensates for the former effects. The optimum alignment
5   position for the silicon nitride waveguide 12 is just below the
centreline of the silicon waveguide 11 as detailed below.

The junction as shown in Figure 2 depicts a standard silicon-on-
insulator waveguide 11 having an end face 13. A layer 14 of
10   silicon nitride which acts as an anti-reflective coating covers
oxide 5 on top of the rib 4. It also covers the end face 13 and
the part of silicon oxide layer 2 which is not covered by the
silicon waveguide 11 and forms an extension with the substrate 3
beyond the end face 13. On top of this layer is a deposited
15   layer of silicon dioxide 16, and on top of this is a layer 17 of
silicon nitride. The centre of the optical intensity profile
through the silicon waveguide 11 and the silicon nitride
waveguide 12 is indicated as a dotted line labelled reference
numeral 18.
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The formation of the junction and the alignment of the two
waveguides will now be explained.

The silicon rib waveguide 11 is formed in the normal way
25   according to the prior art but includes exposing an extension of
the silicon substrate 3 and oxide layer 2 beyond the end 13 of
the waveguide. Photolithography is used to selectively remove
the oxide 5 from the waveguide end face 13. An anti-reflective
silicon nitride layer 14 is deposited over the entire structure
30   at a suitable thickness for maximum effectiveness at the
transmission wavelengths required. In this embodiment the
thickness is approximately 0.16 µm. The next step is to measure
the height of the silicon waveguide 11 to obtain the height of
the centreline above the buried oxide layer 2.   In this
35   embodiment, the silicon waveguide has a height of 4.3 µm above
the layer 2, which means the centreline would be at 2.15 µm.
However, the optimum height of maximum light energy in the

waveguide 11 is slightly lower than this at 1.84 μm. For other embodiments, the optimum height could be determined by simulation or testing. The next step is to deposit over the whole structure a layer of silicon dioxide 16 by PECVD. The thickness of this oxide 16 is carefully controlled to build up a bed over the extended substrate 3 and oxide 2 which has a thickness of 1.74 μm. This means that when the silicon nitride 18 is deposited at 0.2 μm thickness, also by PECVD, it forms a silicon nitride waveguide 12 with a centreline exactly in line with the height of maximum light energy within the silicon waveguide 11 at 1.84 μm above the buried oxide layer 2. Thus the maximum light energy is at line 18 throughout the junction and into the silicon nitride waveguide 12. The silicon nitride waveguide 12 can be patterned lithographically if desired, eg into a ridge or stripe structure.

Figure 3 shows a modified form of the junction in Figure 2 and similar reference numerals have been used for similar parts. In this case the junction is curved to form a convex lens structure at the end of the silicon waveguide 11 and a concave face on the silicon nitride 17 at the junction. The nitride layer 14 and oxide layer 16 each form a curved layer interposed between the convex end face of the silicon layer and the concave end face of the silicon nitride 17. The refractive index of the nitride layer 14 is less than that of the silicon layer 1 so that the curved interface acts as a composite cylindrical collimating lens focusing light in the horizontal plane.

In an alternative embodiment, the silicon oxide 16 and the silicon nitride 18 can be formed using thermal oxidation and LPCVD respectively. The heights of the layers could also be varied. A different dielectric could be used in place of the silicon oxide 16, such as silicon oxynitride or a polymer.

A silicon/silicon nitride waveguide of the type shown in Figure 2 or Figure 3 may be used in an interferometer, such as a Mach-Zehnder interferometer as shown in Figure 4. Such an

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interferometer provides two parallel light paths 40 and 41 between a light source 42 and a light detector such as a photodiode 43. If a phase shift is introduced into the light transmitted by one of the paths relative to the other, either

5 destructive or constructive re-combination may occur or be detected. The path 40 may be provided with a test window 44 for introducing a phase shift dependent on the external refractive index relative to the refractive index within the waveguide forming the part of the path adjacent the window 40.

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In this example, the waveguide extending along the window 44 is formed of silicon nitride with a junction at each end 45,46 to a silicon waveguide as described with reference to Figure 2. The silicon waveguide at each end of the window, and that forming the

15 path 41, may be joined in known manner to optical fibres leading to the detector 43 and from the source 42. A silicon waveguide with a 4 μm rib can be aligned with an optical fibre by undercutting the material which the waveguide is formed on to allow the optical fibre to be brought closer to the end of the

20 waveguide as is disclosed in our US Patent 5787214. This would not be satisfactory with a waveguide of only 0.2 μm height and so the interposition of the silicon waveguides between the silicon nitride region and the optical fibres overcomes this problem.

25 The refractive index of silicon nitride is only 2, compared to 3.5 for silicon. This, together with the geometry used, results in a smaller fraction of the light being maintained within the waveguide. In the case of an interferometer for biosensing this is a useful property, because the waveguide is extremely

30 sensitive to small concentrations of test substances around the sensing window. Furthermore, silicon nitride can be coated with various substances, so that the immediate surrounding of the sensing window can be used to induce a change in the effective refractive index. This is achieved by pre-coating the sensing

35 window with a substance which is known to or expected to react with the substance under test. A typical example would be to coat it with a protein which is known to form a strong bond with

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a particular antibody under test, before immersion in the test substance. If a bonding reaction takes place, the resulting biochemical structure has such a different structure from the protein coating alone that its refractive index is often very
5 different from that of the protein coating alone. Therefore, the proportion of light energy transmitted outside the waveguide changes with the result that a different interference pattern is detected at the right-hand end of the waveguide. This indicates that the particular antibody is present in the test substance.
10 Furthermore, the rate of change of refractive index can be monitored to give an indication of the speed of the bonding reaction. It is of course possible that the refractive index will be changed as soon as the sensing branch is immersed in the test substance even if no bonding reaction takes place, but in
15 general the change is more pronounced if a reaction does take place.

Several of the structures described above can be formed on a single chip which could then be used to test several different
20 substances at once. For example, the window 44 of each structure could be coated with a different protein but then each be immersed in a solution containing different antibodies in order to determine which antibodies are contained in the solution and at what concentration.
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The silicon waveguide used in the reference path 41 may include a modified active region (eg a PIN diode) in which a variable electrical potential is applied to vary the amplitude of light transmitted through the waveguide. In this way, the electric
30 field applied may be varied to maintain a constant light amplitude detectable by the light detector as the relative phases in the two paths varies. The light level selected may be one at which the detected amplitude variation with phase change has the steepest gradient thereby making the interferometer with maximum
35 sensitivity to detection of phase change.

It will be understood that in the manufacture of the structure

shown in Figures 2 and 3 the steps of depositing the silicon nitride layers 14 and 17 involve blanket depositions over the entire area without the need for masking specific areas. Similarly the formation of the oxide layer 16 is a blanket

5   operation over the entire area without the need for masking.

The nitride layer may be left as a blanket layer if the junction is curved to act as a lens as described above. Alternatively the nitride layer may be patterned to form a rib or ridge or a flat

10   stripe.